MESOSCALE STUDY OF A LAKE EFFECT SNOW STORM

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ABSTRACT

During the 1964–65 snow season, the Atmospheric Sciences Research Center, State University of New York (ASRC, SUNY), and the SUNY College at Oswego maintained a mesoscale network of surface pressure, temperature, and wind-recording stations around the eastern end of Lake Ontario to observe the conditions attendant upon lake effect storms on a scale commensurate with storm size. The Cornell Aeronautical Laboratory combined the SUNY data with conventional weather and radar data for the February 3 and 4, 1965 storm period to produce a combination of streamline, isotach, isobaric, and isallobaric analyses from which a number of interesting features became evident.

One important storm characteristic is a narrow confluent-convergent wind shift zone (0.1 to 1.5 n.mi. wide) beneath the snow band. In the storm studied, the wind shift zone was evident beneath the full length of the overland portion of the storm, even when the west-to-east snow band migrated south of the lake. During a period in which two snow bands existed simultaneously, a wind shift line could be observed under each.

Also observed were lee shore pressure patterns that changed in a consistent manner with changes in location of the snow bands. Although lee shore convergence and cyclonic vorticity increases were in evidence throughout the period, these patterns did not appear to be directly related to the snow bands. The analyses strongly suggest that while the formation of the lake effect bands is caused by heating of the air by a warm lake, the location and movement of the bands are controlled by winds aloft, rather than by surface conditions.

1. INTRODUCTION

Western New York State is one of the areas of heaviest snowfall east of the Rocky Mountains, with some locations receiving from 150 to 200 in. of snow a year. Much of this snow and most of the severe snow storms this region experiences can be traced to the influence of Lakes Erie and Ontario which act as heat and moisture sources when cold polar or Arctic air moves into the area. Such "lake effect" storms or their consequences have been described by several authors [1, 2, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18], but no study to date has provided sufficient quantitative observational information to determine the nature of the storms or their immediate environment.

Lake effect snow storms are not unique to Lakes Erie and Ontario, for all of the Great Lakes produce such storms and each has its "snowbelt area." Furthermore the Japanese experience storms of strikingly similar character with outbreaks of Arctic air across the Sea of Japan [3, 4].

Lake effect storms are banded cloud structures like those described by Kuettner [6] and Kuo [7], and lapse-time photographs show that they have a strong resemblance to Bénard-cell convection. However, lake effect storms generally consist of only a single band of cumulus congestus cells, with two bands occasionally coexisting over a single lake. They are truly a mesoscale phenomenon with representative dimensions of 2 to 20 mi. width and 50 to 100 mi. length. This small size, coupled with their predominant location over water, has generally frustrated attempts to determine the physical nature and environment of this type of storm.

During the 1964–65 snow season, the Atmospheric Sciences Research Center, State University of New York (ASRC, SUNY) and the SUNY College at Oswego maintained a mesoscale observing network of 14 anemometers, 9 hygrothermographs, and 49 microbarographs around the eastern end of Lake Ontario to observe lake effect storm conditions [16]. The data acquired by these stations, augmented by data from one temperature and two wind-recording stations maintained near Oswego by the Niagara Mohawk Power Corp., provided a unique opportunity to study the surface conditions attendant upon such storms in a scale commensurate with their size. The ASRC data from a two-day storm period were reduced by personnel at the College at Oswego and analyzed at

Cornell Aeronautical Laboratory in a joint ASRC-CAL Project. The results of this analysis provide a picture of the surface conditions associated with lake effect storms in a detail never before possible.

2. MACROSCALE STORM ENVIRONMENT

The period of February 3–4, 1965 was chosen from the data acquired by ASRC for the cooperative ASRC-CAL study primarily because radar and human observations of the storm, together with the macroscale synoptic conditions for these two days, appeared typical of those associated with western New York lake effect storms.

Between 1300 EST February 1, and 0100 EST February 2, 1965, a continental Arctic cold front moved eastward over Lakes Erie and Ontario. Before the front had completed its traverse of the lakes, one of the most reliable large-scale indications of lake effect storm conditions had begun to develop, namely a surface pressure trough over the Great Lakes caused by heating of the cold air over warm lake water [11]. The trough first appeared as a westward extension of the frontal low-pressure center, but it remained over the Great Lakes after the parent low moved off the east coast. Figure 1 shows the gross features of the surface synoptic situation as they appeared at 0100 EST February 4, midway in the period of study. The frontal low was located over the North Atlantic by map time, but the typical lake-induced pressure trough dominated the whole Great Lakes area. When more detailed macroscale analyses were drawn for the storm period, the maps still retained characteristic features associated with lake effect storm situations. McVehil and Peace [9] have described short-wave pressure development and strong cross-isobaric surface flow to the lee of each of the Great Lakes in such

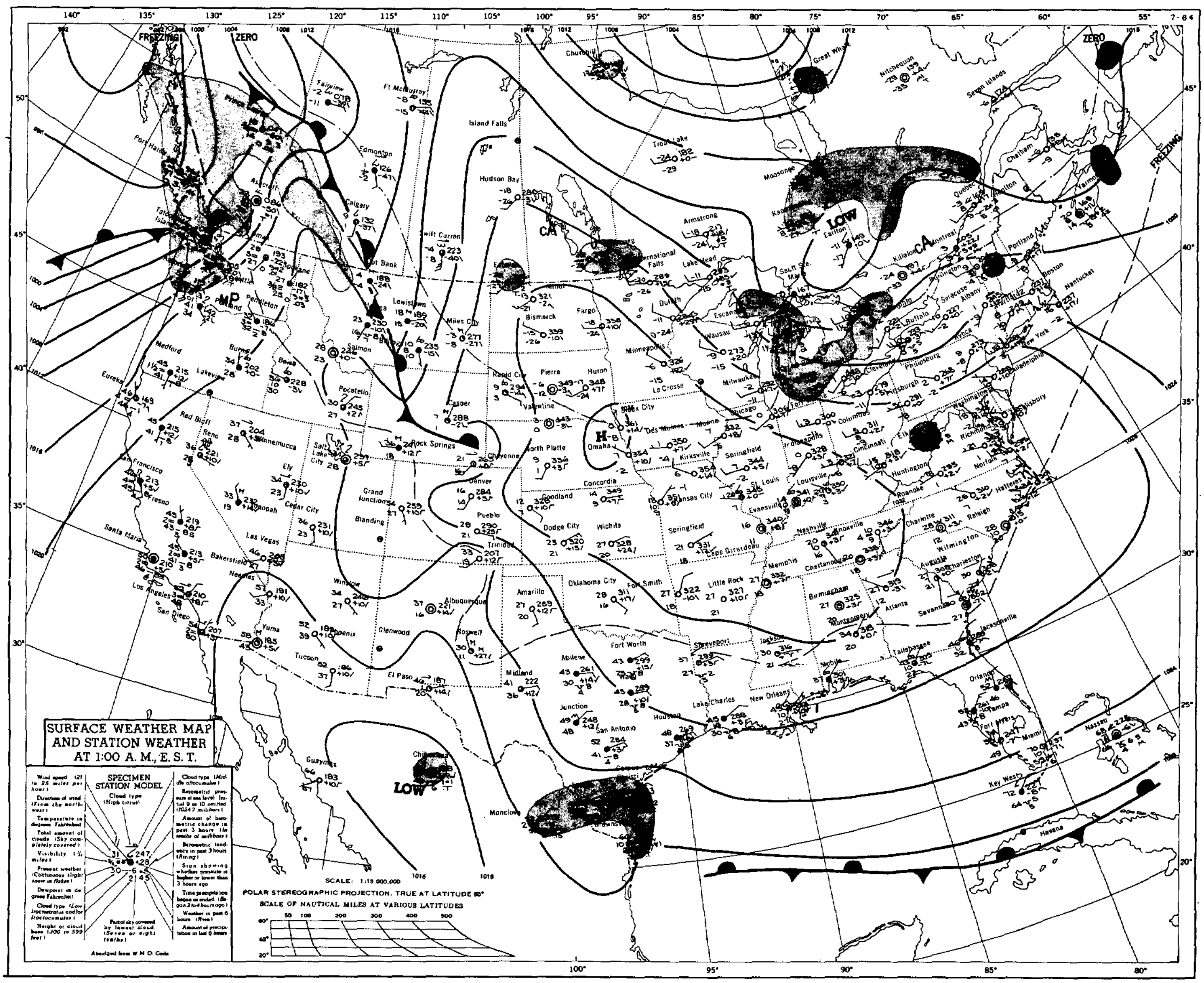

FIGURE 1.—The U.S. Weather Bureau *Daily Weather Map* for 0100 EST, February 4, 1965.

storm situations. Figure 2 shows the detailed macroscale surface pressure and wind conditions over the Great Lakes at 0100 EST February 4. This map is typical of conditions during the 2-day storm period studied.

3. RADAR CHARACTERISTICS

The most definitive observations of lake effect storms have, in the past, been provided by radar. In this study, the PPI-scope film record of the Buffalo, N.Y. Weather Bureau's WSR–57 radar proved indispensable in determining the character, position, dimensions, and movement of the subject storm, although its eastern extremity (east of Lake Ontario) was beyond range of the Buffalo radar (figs. 2 and 3a). Lake effect snow bands are characteristically shallow systems with radar-detectable tops usually lying below 10,000 ft. As a result, the line echo of the snow band was observable to the 100-n.mi. PPI-scope range of the Buffalo radar only during the storm's more intense periods, and was never observable at the range of most of the surface observing stations. However, other reliable observations confirm that the snow band extended well beyond the range of the Buffalo radar throughout the 2-day period of the study. The observed echo lines were essentially straight (figs. 3b–3i), and linear extrapolation of the observed echoes was found to position the storm in agreement with the numerous observations made around the eastern end of Lake Ontario.

Figures 3b–3i show selected stages in the life of the storm. These pictures were chosen from a 6-min. interval lapse-time film covering essentially the full storm period, with the exception of the interval between 0408 and 0636 EST on February 4. This film was augmented by hourly polaroid scope photographs provided for this study by the Buffalo USWB office. The persistent line echo southwest

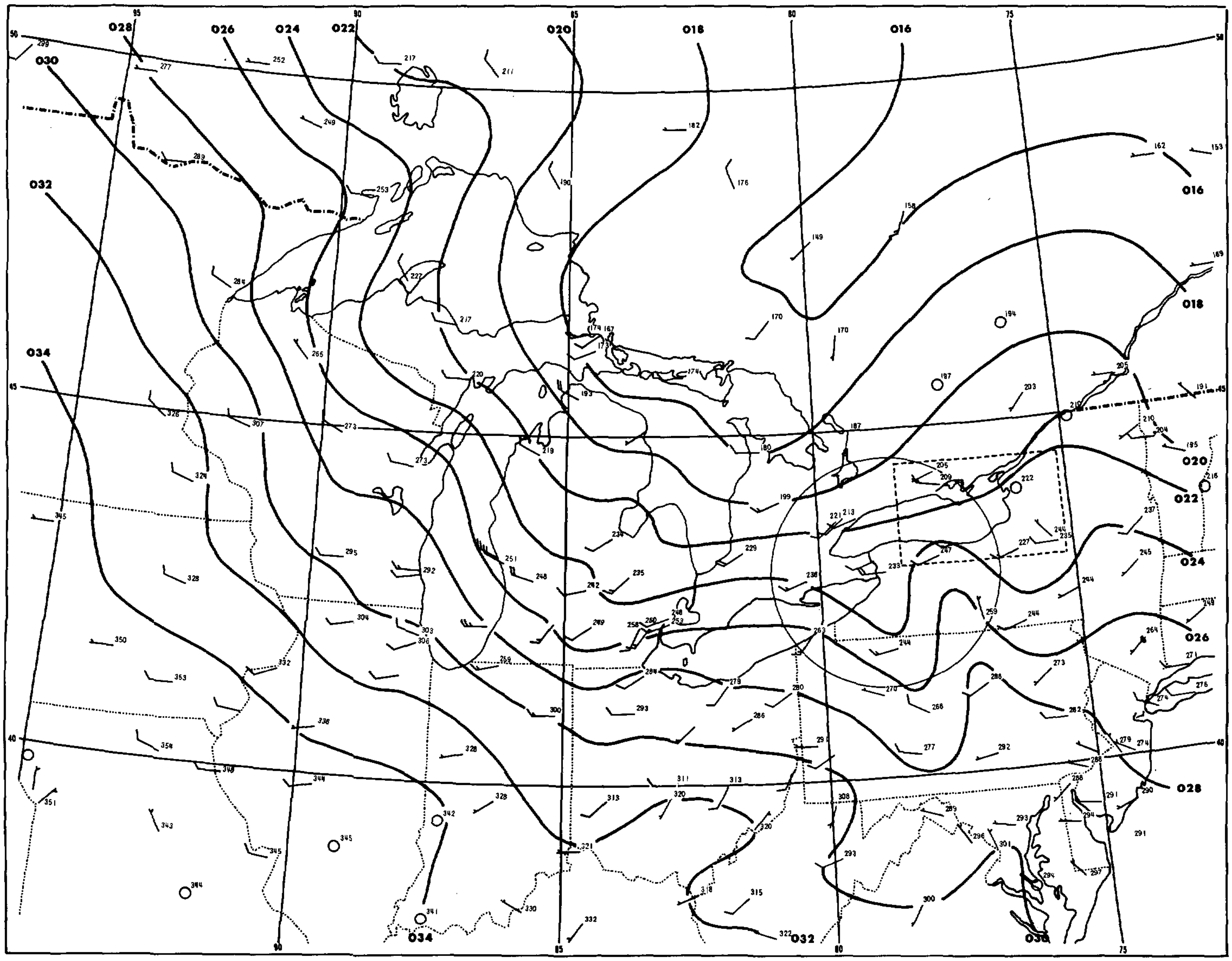

FIGURE 2.—Surface isobars and winds for 0100 EST, February 4, 1965. The circle centered on Buffalo, N.Y. is the area covered by the Buffalo, N.Y. WSR–57 radar at the 100-n.mi. range. The rectangle over and east of Lake Ontario is the area covered by the mesoanalysis maps.

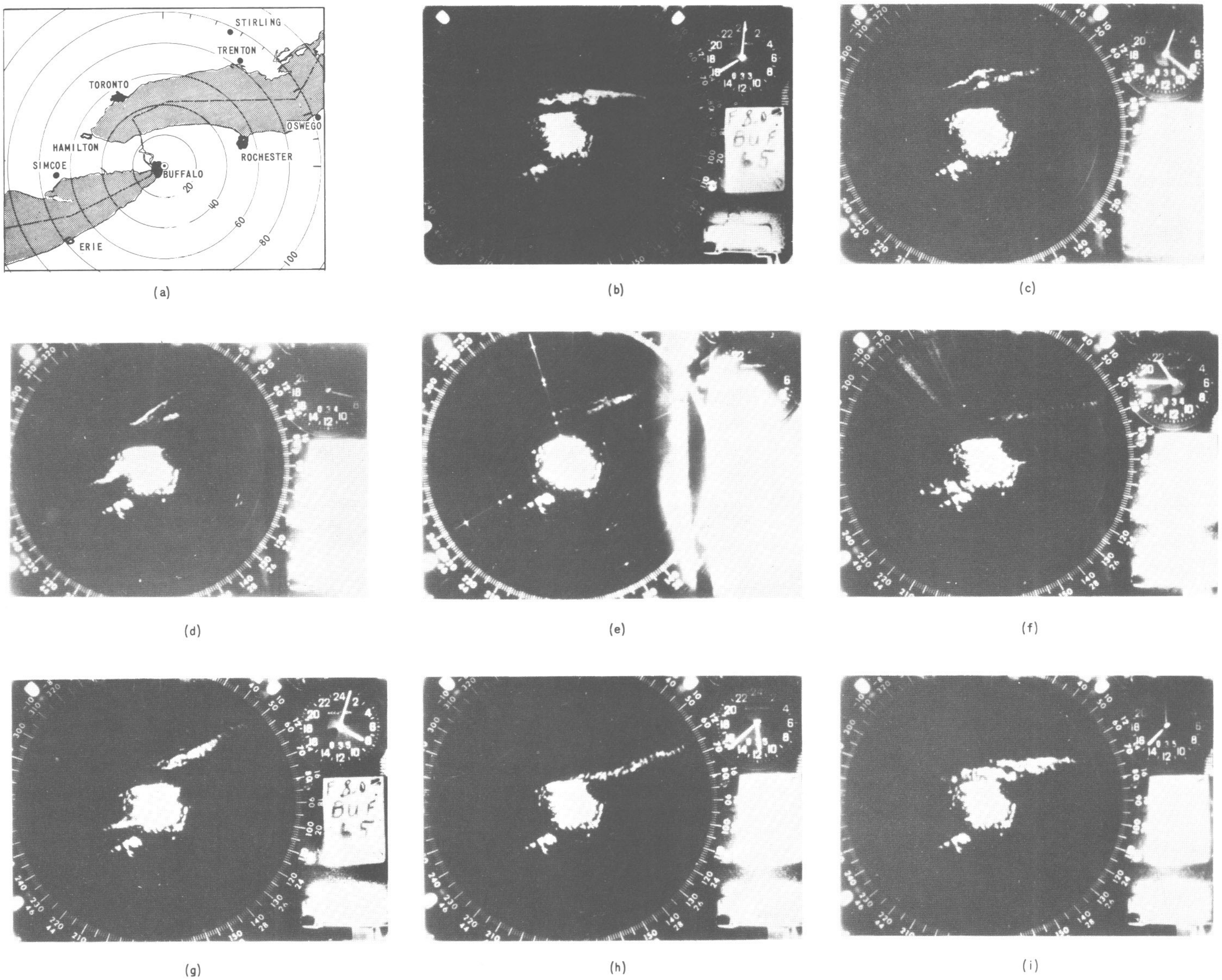

FIGURE 3.—A radar chronology of the Lake Ontario storm: (a) the area covered by the WSR-57 radar at Buffalo, N.Y. at the 100-n.mi. range, (b) the shoreline band echo as it appeared at 1802 EST, February 2, 1965, (c) the double line echoes at 0123 EST, February 3, (d) the double Lake Ontario line echoes and the Lake Erie line echo at 0657 EST, February 3, (e) the merging Lake Ontario line echoes and the Lake Erie line echo (emerging from ground clutter at 250°) at 0939 EST, February 3, (f) the Lakes Erie and Ontario line echoes at 2145 EST, February 3, (g) the two line echoes at 0802 EST, February 4, (h) the Lake Ontario line echo at 1143 EST, February 4, (i) the shoreline band echo at 1459 EST, February 4. Scope range is 100 n.mi. and antenna elevation is 1° in all photographs.

of Buffalo in all photographs is the return from a row of hills just onshore of the eastern end of Lake Erie, and should not be confused with a Lake Erie snow band that was also present when photographs 3d–3g were taken.

The Lake Ontario storm of February 2, 3, and 4, 1965 characteristically changed location, orientation, or character several times during its lifetime. On the 2d, the snow band formed and remained confined over the southern shore of the lake, where it produced snow at both Syracuse and Rochester, N.Y. for most of the day. Figure 3b shows the radar characteristics of the storm during this period when it corresponded to what McVehil and Peace [9] have referred to as a single "shoreline band." Such single shoreline bands occur over and parallel to a downwind shore when the winds aloft are directed onshore at a small angle. The 4,000 to 10,000-ft. winds aloft at Buffalo were 280° to 290° until 1900 EST on the 2d, and the echo line lay along the west-to-east shoreline, as shown in figure 3b.

At 1900 EST on the 2d, the Buffalo radiosonde revealed a wind shift to 260° below 8,000 ft., and the Lake Ontario storm subsequently began moving northward over the lake, changed orientation, and changed character to an "overlake band" [9]—one with an orientation approximately parallel to the winds aloft above the gradient wind level. Figures 3c–3h show the overlake snow storm that existed over Lake Ontario (and onshore at its downwind end) from about 2000 EST on the 2d to 1300 EST on the 4th.

During the early hours of February 3, a second line echo became evident north of the original one, and the two approximately parallel lines coexisted for several hours (figs. 3c, 3d, and 3e). After formation, the second line echo rotated slowly counterclockwise for 35° while the older echo line rotated less than 10°. No reproducible PPI-scope photographs are available for the 0530 to 0630 EST period when the bands were farthest apart, but figure 3d shows the two lines at 0655 EST as the northern line rotated back toward the original line. The northern line subsequently merged with the quasi-stationary southern line (fig. 3e), and the resultant single line continued a southward migration.

The existence of the southern snow band beyond the line echo detected by radar (fig. 3d) is testified to by a narrow belt of snow that fell on and south of Watertown, N.Y. (135 n.mi. at 60° from Buffalo) from 0220 until 1328 EST. The northern band deposited snow on Trenton, Ontario (fig. 3a) from 0520 until 0650 EST, while the northern radar line echo was directed toward that station.

The line echo located just northwest of Buffalo in figure 3d is a Lake Erie snow band that was depositing snow on Niagara Falls, N.Y. at the time of the photograph. Like the northernmost Lake Ontario snow band, the Lake Erie band rotated counterclockwise prior to 0600 EST (shifting the snowfall from Buffalo to Niagara Falls), and then clockwise (shifting the snowfall back to Buffalo). The Lake Erie line echo is a barely detectable extension of the ground return at 250° in figure 3e, but is quite prominent southwest of Buffalo in figures 3f and 3g.

During the daylight hours of the 3d, both the combined Lake Ontario snow band and the Lake Erie band continued to rotate slowly clockwise until the Lake Ontario storm was oriented along a 260° to 080° line just north of the southern shore of the lake (fig. 3f). The band then remained stationary for about 6 hr. during which time it produced snow along a line east of the lake as far inland as Boonville, N.Y. (155 n.mi. at 77° from Buffalo and directly along an eastward extension of the line echo in fig. 3f).

In the early morning hours of February 4, both the Lake Erie and the Lake Ontario line echoes rotated counterclockwise again and became stationary in a 240° to 060° orientation (fig. 3g). Later in the morning, the Lake Erie storm dissipated and the Lake Ontario band again rotated clockwise (fig. 3h). About 1300 EST, the winds aloft veered to 280° and 290° and the Lake Ontario storm changed to a shoreline band similar to that on February 2. The radar echo of the shoreline band typically appeared as in figure 3i until the band dissipated late on February 4.

4. THE ANALYSIS

Isobaric, isallobaric, streamline, isotach, and horizontal divergence analyses were performed for the 3d and 4th of February. The ASRC data were augmented by hourly and special observations from United States and Canadian weather stations, one Canadian wind-recording site (59 on maps), and two observing sites maintained by Niagara Mohawk Power Corp. Only seven hourly reporting manned stations lie in the mesoanalysis map area (stations labeled with letters in the figures), but many more were utilized to establish map boundary conditions through macroscale analyses of the area surrounding the mesoanalysis map. Where data were either sparse or nonexistent, such as over the lake itself or along the western map boundary, the analyses represent interpolations of conditions observed on shore or at stations such as Toronto, Hamilton, Niagara Falls, and Buffalo that do not appear on the map. All such interpolations were drawn to agree with the radar location of the storm over the lake.

The analyses are basically synoptic, but the movement of the Lake Ontario snow band north and south through the ASRC network allowed the utilization of recorded time variations of elements to refine the details of the horizontal distribution of these elements. The movement of the snow band (or bands) north and south twice during the period of analysis also provided two samples of data for almost every stage of the storm. All major features of the analyses for corresponding band locations and movement were found to be essentially the same for the two days, so only a few samples of the analyses are needed to demonstrate these features.

WIND ANALYSIS

Throughout the storm, the most persistent analyzed features were the distinct wind-shift line and the confluence-convergence zone beneath the northern edge of the snow band. When the snow band passed wind-reporting stations (fig. 4) wind shifts of 25° to 90° were recorded in a few minutes, with the majority amounting to 30° to 40°. Figures 5 and 6 are the streamline and isotach analyses for 1200 and 2100 EST on February 3. At 1200 EST (fig. 5), the snow band lay over Pt. Petre, Ontario (Station 60) and Watertown, N.Y. (Station ART). Buffalo radar confirmed the existence of the line echo over Pt. Petre and its orientation in a line toward Watertown, while Watertown reported a ceiling of 300 ft. obscured and ¼ mi. visibility in snow and blowing snow.

The wind shifted from 255° to 290° in less than 5 min. at Pt. Traverse (58) at 0930 EST, and from 255° to 280° in an equally short time at Pt. Petre (60) at 1240 EST. It took the wind-shift line 3 hr. and 10 min. to move approximately 3½ n.mi. normal to the axis of the radar line echo in this area. This agrees with the movement of the line echo itself. A comparison of the 5-min. wind shift and the wind-shift line speed implies that the wind differences existed over a distance of only $\frac{1}{10}$ n.mi. The

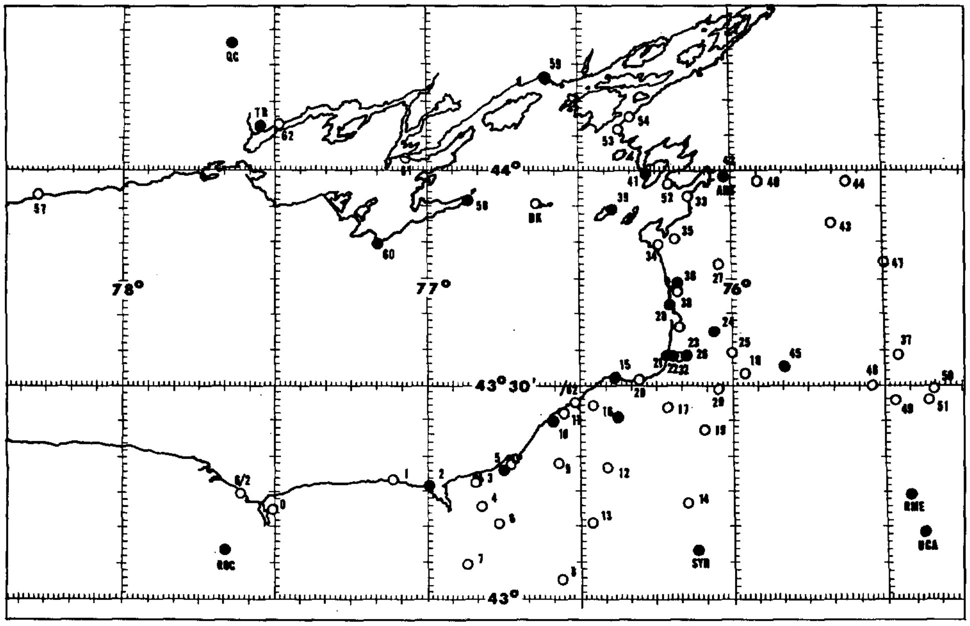

FIGURE 4.—Mesoscale map area. Lettered stations with filled circles are the United States and Canadian hourly reporting stations. Station 59, Kingston marine station, reports prevailing wind direction and total number of miles of wind for each hour. Station 15 and the dot 5 n.mi. south of 15 are Niagara Mohawk Power Corp. observing stations. The 14 remaining dots represent ASRC wind-observing sites. No speed was recorded at ASRC sites 22 and 23 during the study period.

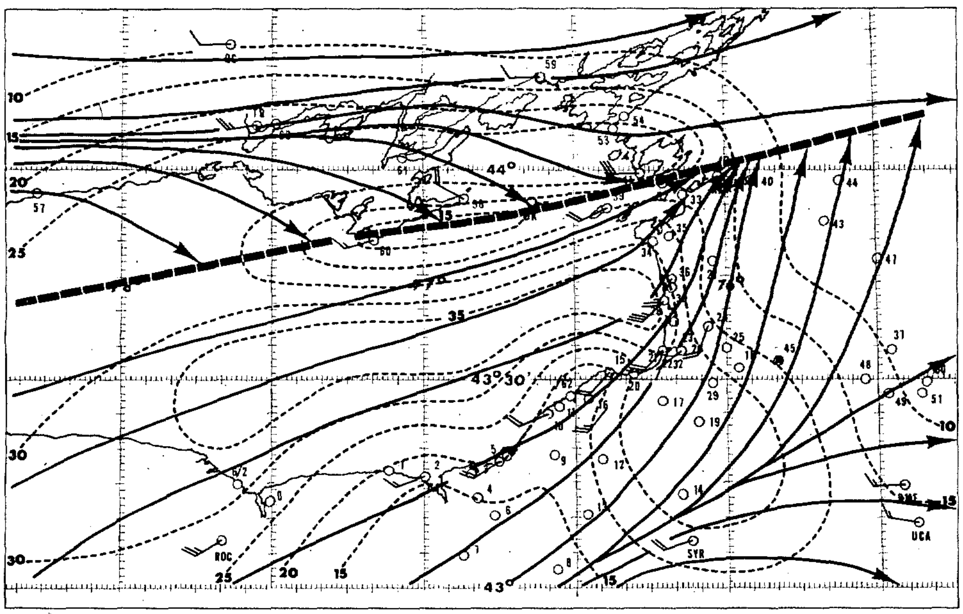

FIGURE 5.—Mesoscale streamline and isotach (m.p.h.) analysis for 1200 EST, February 3, 1965.

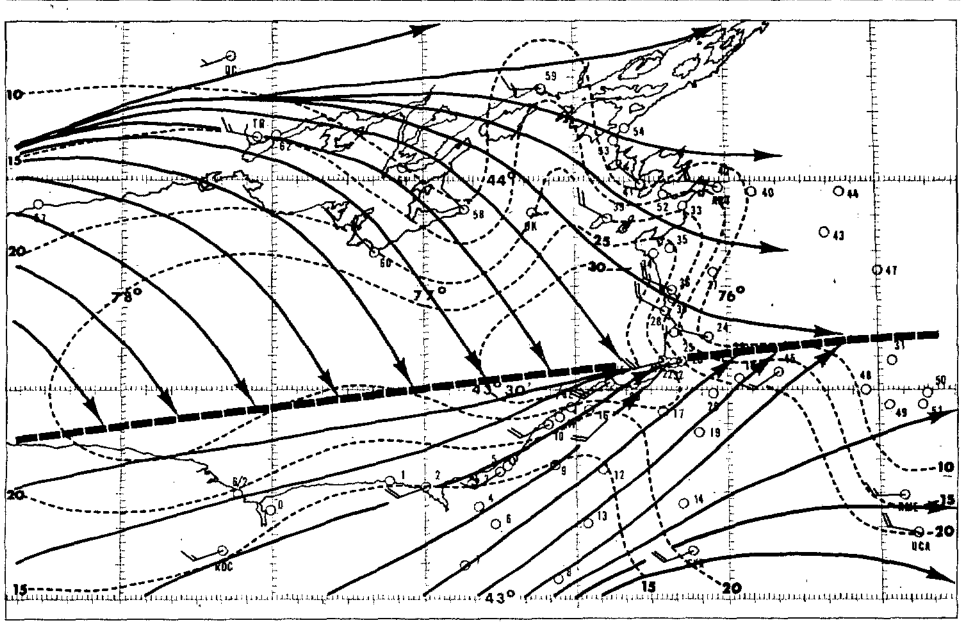

FIGURE 6.—Mesoscale streamline and isotach (m.p.h.) analysis for 2100 EST, February 3, 1965.

wind-shift line passed the Pt. Peninsula Isthmus station (41) at 1120 EST with a wind direction change from 235° to 280° in less than 5 min., and subsequently passed Galloo Island (39) at 1345 EST with another 5-min. shift, this time from 250° to 280°. The distance between these two stations, measured normal to the line echo, is approximately 5½ n.mi. If we can assume all time variations in wind were due to the movement of the convergence line, this means a wind direction difference of 30° to 45° over a distance of ⅕ n.mi. The same technique was used to compute the width of the wind-shift line as it moved from station to station through the ASRC network during the remainder of the 2-day study period. The line varied in width from a fraction of a mile to a maximum of 1½ n.mi. These line widths may be in error by a factor of two or so, because of the inability to resolve time intervals of less than 5 min. from the wind traces, but they demonstrate how extremely narrow the wind-shift line was in this storm. Experience in other such storms from both Lakes Erie and Ontario indicates that the storm was not unique in this respect.

The snow band continued southward with individual radar echoes moving eastward along the line until it became stationary over ASRC stations 21 and 26 (fig. 6). The wind at these stations veered 25° and 30° to 255° and 260°, respectively, and stopped short of the 285° to 300° recorded at more northerly stations. The wind remained southwest at stations 15 and 45, and all stations farther south. At the time of figure 6 (2100 EST), both Watertown (ART) and Utica (UCA) reported only scattered clouds and Syracuse (SYR) was clear. Meanwhile, the ASRC cooperative observer at Orwell (25), just south of the wind-shift line, recorded that snow began at 1920 EST with 2½ in. of new snow by 2145 EST and 9 in. by 2335 EST. Livingston Lansing of ASRC recorded that snow began at Boonville (50) at 2015 EST. Boonville received 7 in. of new snow, and Bennet's Bridge (18) reported 6 in. before the line moved back north during the early hours of the 4th. The wind-shift line never reached as far south as Bennet's Bridge or Boonville, so the snow fell south of the wind-shift line as it had at Watertown earlier. At Watertown, the end of the snow and the wind shift occurred within the same hour.

Over the lake and north of the radar line echo, isogons (and the resulting streamlines) and isotachs for all streamline maps were drawn to agree with the time variation of wind at stations 39, 58, 59, 60, TR, and QC. Over the lake and south of the radar line echo, streamlines were drawn approximately parallel to the reported wind directions south of the lake. This assumption of uniform wind direction south of the overlake portion of the storm was based on the observation that the winds at stations 39, 58, and 60 agreed with those south of the lake whenever the radar line echo (or its eastward extension) lay over or north of these stations.

Overland, streamline analyses were constructed from isogons drawn to agree with the time variation of wind

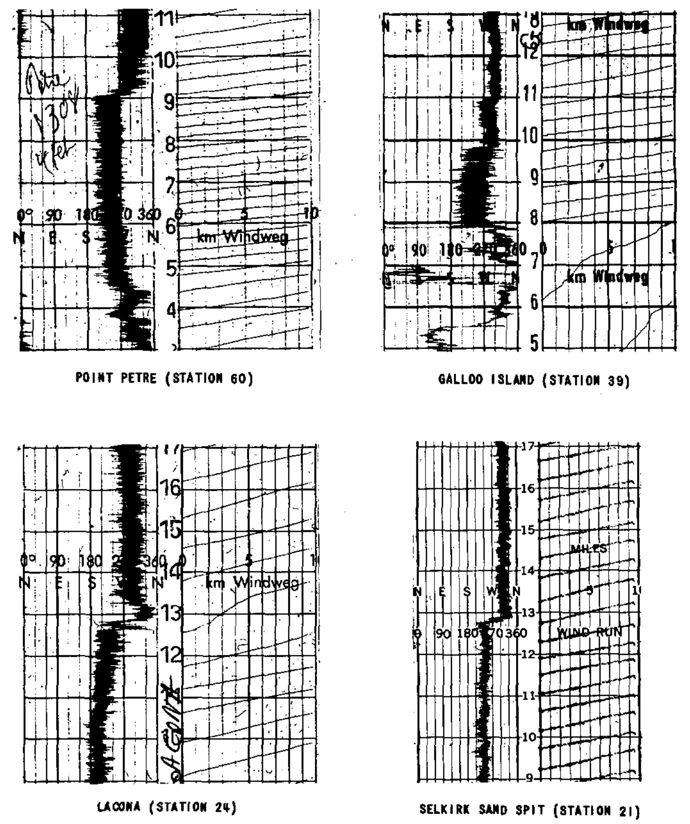

Figure 7.—Abstracts of the February 4, 1965 wind traces from four ASRC sites.

direction at stations near the wind-shift line. However, the sharpness of the confluence line over land is evident from the synoptic differences in wind direction alone. Moreover, the configuration of the streamlines and the isotach field show not only sharp confluence, but the presence of convergence as well. The streamlines north of the overlake portion of the confluence line show active inflow into the convergence zone, while those to the south are passively involved. East of the lake, the situation appears partially reversed. The northern flow participating in the convergence was limited to the area just north of the lake, while the southern streamlines were consistently oriented southwest well into Pennsylvania. This tendency for the flow over the lake from the north to be limited, while that from the south is consistent for great distances upwind, is a feature that has been observable even in detailed macroanalyses [9].

After its northward migration during the early hours of the 4th, the snow band remained stationary in the Pt. Petre (60)–Pt. Traverse (58), Ontario region for about 4½ hr. Figure 3g shows the radar character of the storm during this stationary period and figure 7 shows four sample wind traces for the period when the band passed each of the stations on its way south for the second time. The Pt. Petre wind trace shows both the northward passage of the band at 0430 EST and the subsequent southward passage at 0910 EST. During the interim, the wind-shift line reached (but never passed) Pt. Traverse.

FIGURE 8.—The lake effect cloud band at 1130 EST, February 4, 1965. The photograph was taken from the vicinity of Point Traverse, Ontario (station 58) looking south.

Personal observations by Sykes in the Pt. Petre–Pt. Traverse area on the morning of the 4th revealed that the snow reached only 2 or 3 mi. north of the Pt. Traverse latitude. The snow was heaviest south of the wind-shift line, where a measured 14 to 15 in. of new snow accumulated before the band again moved southward.

About the time when the snow band was over mid-lake on its way south, the photograph in figure 8 was taken, looking southward from near Pt. Traverse. The line of cell-like radar echoes in figure 3h corresponds to the line of cumulus congestus cells in the photograph. The cumulus cells were topped by a cirrus veil that is not evident in this black and white copy of the original color photograph. The clearcut wall of the cloud in figure 8 is typical of the appearance of lake effect storms viewed from the north. Photographs taken from Oswego (11) at the same time showed that a broken deck of stratocumulus extended from the snow band to south of Oswego.

The distribution of velocity divergence in the area of study was determined independently of the streamline and isotach analyses. Divergence calculations were made using the expression for horizontal velocity divergence.

$$\text{div }\mathbf{V}_h=\frac{1}{\delta A}\frac{\partial(\delta A)}{\partial t}\approx\frac{1}{A_0}\frac{(A-A_0)}{\Delta t}$$

A_0 was taken as the triangular area formed by the locations of three wind-observing stations, and A as the triangular area formed by the terminal locations of air parcels from each station advected with the stations' mean wind velocities for the time interval Δt (taken at 15 min.). Numerous combinations of stations were used for calculation, and the result was a set of objective areal distributions of horizontal velocity divergence. The magnitudes of divergence are sensitive to the size of the area used for the calculation, so the values had to be viewed with some discretion. Nonetheless, the general features were very evident. Maximum convergence (negative divergence) occurred along the snow band wind-shift line with divergence values generally -5 to -9×10^{-4} sec.$^{-1}$. At 1200 EST (fig. 5), the three triangular areas enclosed by stations 58, 41, ART, 39, and 60 had a computed divergence of -7 to -9×10^{-4} sec.$^{-1}$, while values of -5 to -7×10^{-4} sec.$^{-1}$ were calculated for the triangular areas enclosed by stations 28, 24, 45, and 15 in figure 6. Divergence of $+5\times10^{-5}$ to $+7\times10^{-4}$ sec.$^{-1}$ was present north of the overlake portions of the storm, while a large region of $+5\times10^{-5}$ to $+2\times10^{-4}$ sec.$^{-1}$ persisted southeast of the lake.

The whole region east of the lake continuously exhibited divergence of -1 to -5×10^{-4} sec.$^{-1}$. The streamline and isotach analysis for 1200 EST (fig. 5) shows a general cyclonic curvature and convergence in this region in agreement with the calculations, but snow was confined to within a few miles south of Watertown this early in the day. When the storm band was stationary through stations 21 and 26 at 2100 EST, a similar condition again prevailed (fig. 6); distinctly anticyclonic flow north of the snow band increased vorticity to cyclonic flow along the eastern shore of the lake. Again, it is of interest to note that, though the streamlines show an increase in vorticity in response to the speed convergence north of the snow band, the only snow was occurring along the west-to-east confluence-convergence line normal to the eastern shore. In the past, frictional convergence, orographic lifting, or land breeze convergence along the downwind shore have been cited as causes of lake effect snow. Petterssen and Calabrese [11] postulated that lake effect snow was due to thermal convergence and lift along the downwind shore. On both days of the overlake stage of this storm, the suspected convergence did apparently exist all along the downwind shore, but it was neither related to the snow nor of the same character as the convergence beneath the snow band.

PRESSURE ANALYSIS

The least-expected features to appear in the analysis were the pressure patterns. Examination of individual microbarograph charts, both in the past and in this case, revealed no distinctive pressure features. Nonetheless, the pressure data from the ASRC microbarographs were processed and plotted, and isobaric and 3-hr. isallobaric analyses constructed. A correction for each microbarograph was derived from the data available from the 17 United States and Canadian manned weather stations nearest Lake Ontario. The average of 24 hourly altimeter settings for February 3 was computed for each manned station and a smooth isobaric analysis drawn. The average of 24 hourly values from each ASRC microbarograph was calculated and compared with the average altimeter setting value at its site on the mean pressure map. The difference between the analyzed and computed value of the average pressure was used as a correction factor for each ASRC microbarograph.

Figure 9 shows the pressure pattern (corrected altimeter

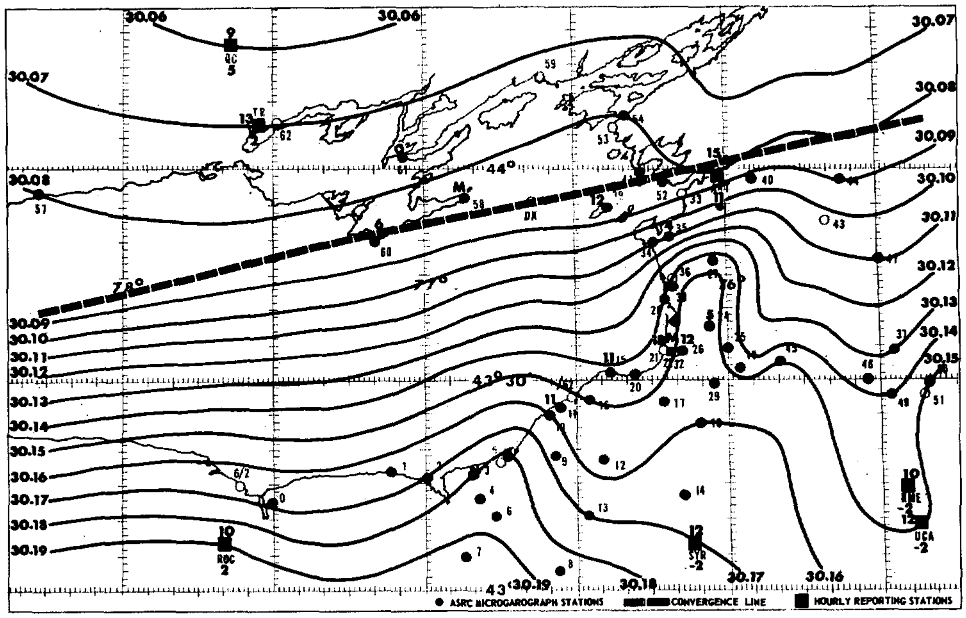

FIGURE 9.—Mesoscale isobaric analysis (altimeter setting) for 1200 EST, February 3, 1965. The location of the convergence line is based upon the streamline analysis and location of the radar echo over the lake. The numbers above stations are temperatures (°F.) and those below hourly reporting stations are dew point temperatures (°F.). Lake Ontario was essentially ice-free with a water temperature of 36°F. at Oswego, N.Y. (station 11).

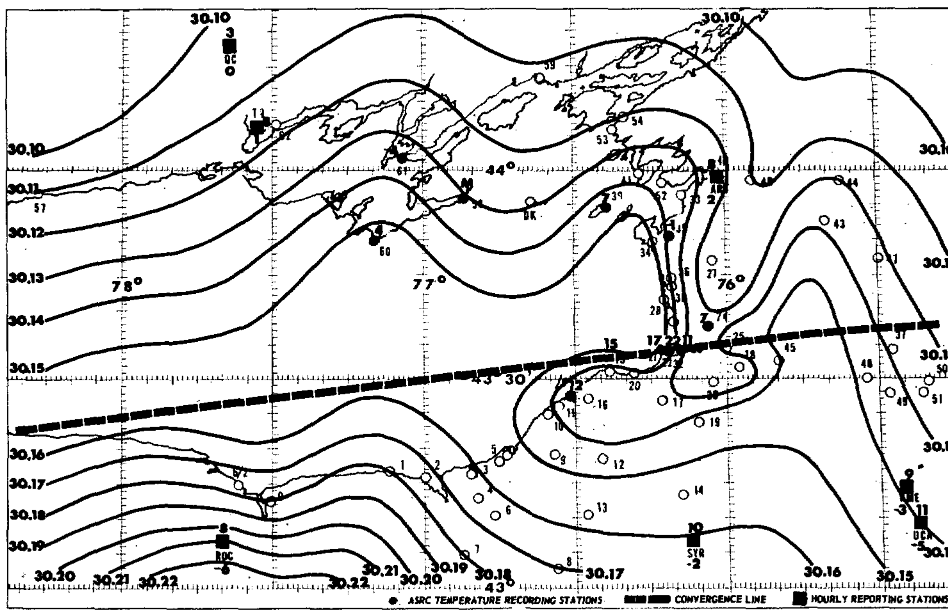

FIGURE 10.—Mesoscale isobaric analysis (altimeter setting) for 2100 EST, February 3, 1965. The location of the convergence line is based upon the streamline analysis and location of the radar echo over the lake. The numbers above stations are temperatures (°F) and those below hourly reporting stations are dew point temperatures (°F.). Lake Ontario was essentially ice-free with a water temperature at 36°F. at Oswego, N.Y. (station 11).

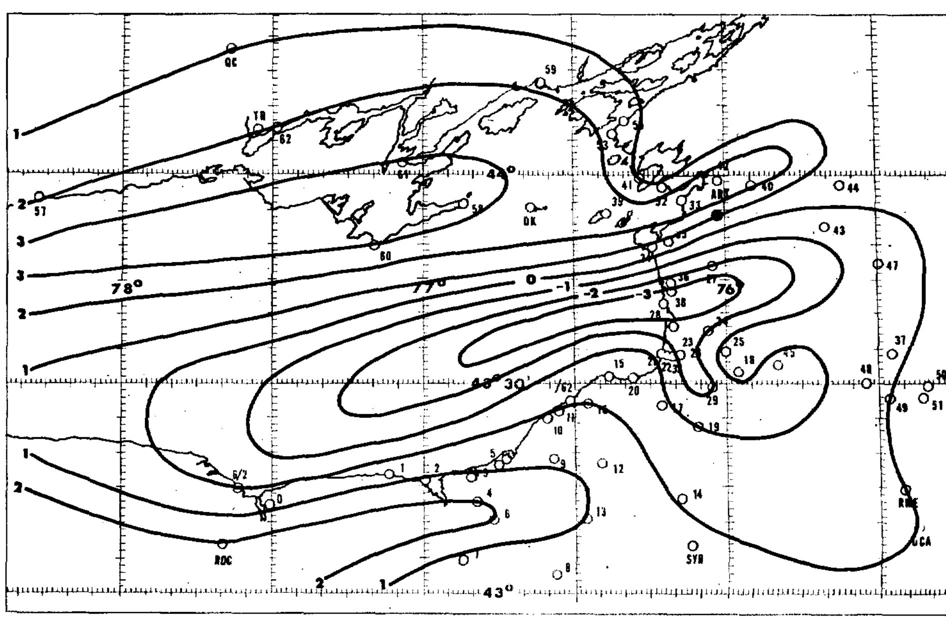

FIGURE 11.—Three-hour isallobaric analysis (0.01 in. of Hg) for 1200 to 1500 EST, February. 3, 1965. The dot south of ART is Adams Center, where Sykes observed the most intense part of the storm's passage at 1508 EST.

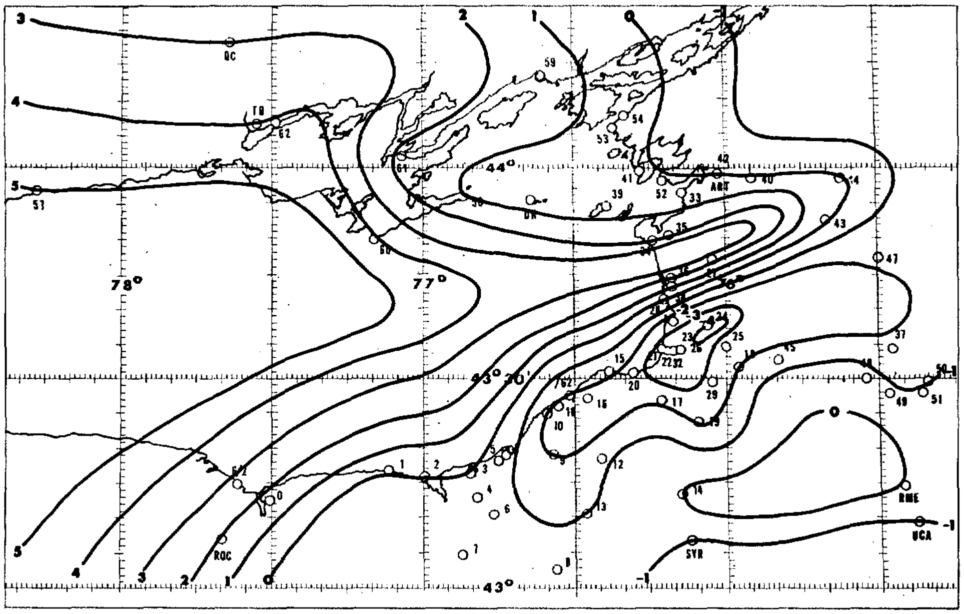

FIGURE 12.—Three-hour isallobaric analysis (0.01 in. of Hg) for 0900 to 1200 EST, February 4, 1965.

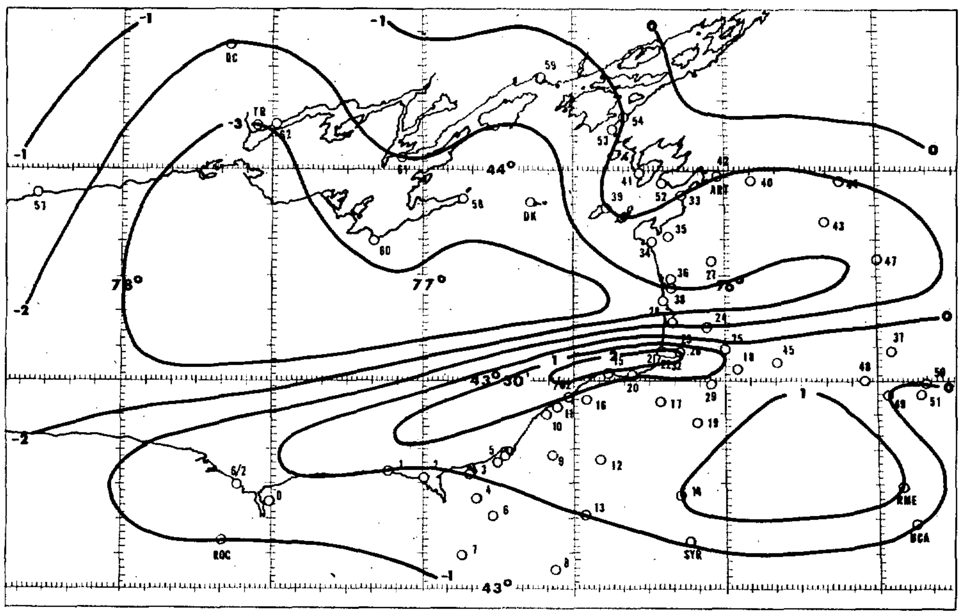

FIGURE 13.—Three-hour isallobaric analysis (0.01 in. of Hg) for 0300 to 0600 EST, February 4, 1965.

setting) for February 3 at 1200 EST. The pressure ridge east of the lake was present for the early hours of the 3d and reappeared when the snow band was again in a similar location early on the 4th. As the snow band migrated southward during the succeeding nine hours, this ridge flattened and then was gradually transformed into the trough shown in figure 10 for 2100 EST. A similar trough was much in evidence when the snow band was again in this region around 1200 EST on the 4th. The trough persisted and extended around to the south shore after the storm changed to a shoreline band over and south of the south shore on the afternoon of the 4th.

One of the most puzzling features of the mesoanalysis was the contrast in pressure gradient north and south of the overwater portion of the snow band. These pressure gradients were drawn as extensions of the gradients north and south of the lake and in agreement with stations west of the map area. All pressure analyses showed a distinctly stronger pressure gradient south of the snow band than north. With the basic south-to-north pressure gradient present throughout the analysis period, this contrast of gradient magnitudes implies a density discontinuity across the convergence line with colder, denser air to the north [5]. A frontal type of structure associated with lake effect storms is not unlikely in itself, especially with the strong convergence present, but there is no surface temperature or dew point evidence to support such a density contrast. No isothermal analyses are presented because some of the ASRC thermographs were inoperative during this period, and others were obviously in error. Nonetheless, temperatures and dew points were studied for evidence of density contrast and none was found.

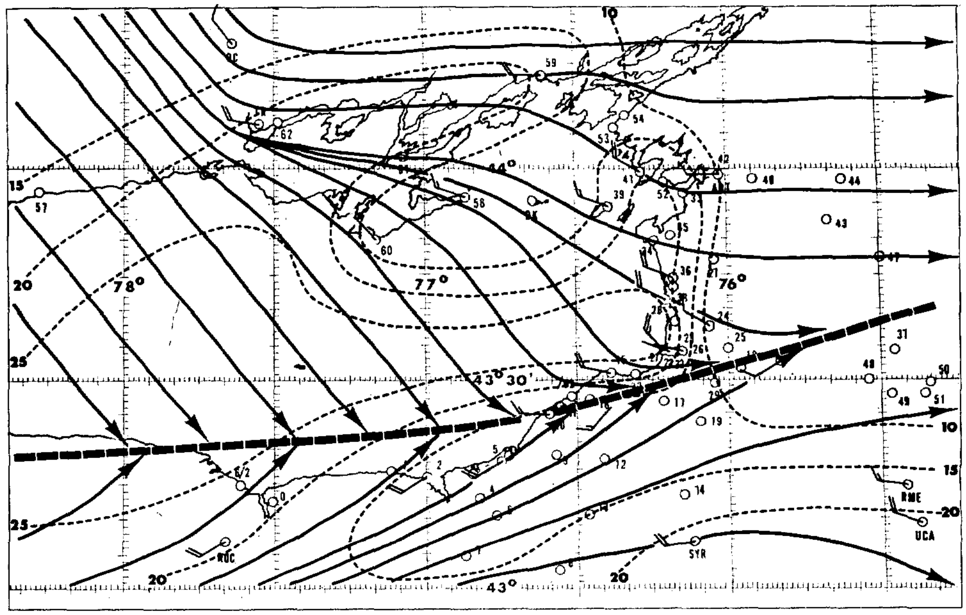

FIGURE 14.—Streamline and isotach (m.p.h.) analysis for 1500 EST, February 4, 1965.

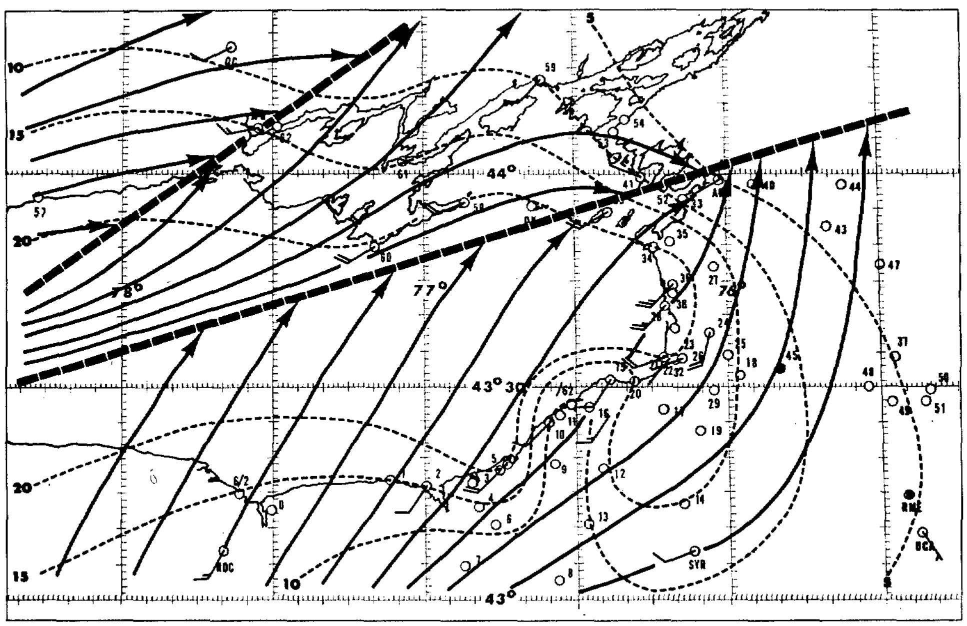

FIGURE 15.—Streamline and iostach (m.p.h.) analysis for 0600 EST, February 3, 1965.

Temperatures at stations like Buffalo, Rochester, Syracuse, Utica, Oswego (11), and Nine Mile Point (15) south of the lake agreed as closely with Toronto, Trenton, and Sterling, Ontario as they did with each other (figs. 9 and 10). When the snow band passed Watertown, N.Y., or one of the ASRC thermograph stations, no persistent temperature change was discernible. Temperatures generally fell with onset of snow, but returned to their original value after it ended. The only persistent temperature contrast observed was the expected increase in temperature with proximity to the warm (36° F.) lake or with a local wind shift from a land-to-water trajectory.

The 3-hr. isallobaric analyses showed distinctive patterns during periods of band movement. From 0600 EST until about 2100 EST on the 3d, and from 0900 EST to about 1500 EST on the 4th, the band was in motion southward. All of the 3-hr. isallobaric charts for these periods revealed an approximately west-to-east line of maximum pressure fall, or minimum pressure rise, south of the snow band, and a line of maximum pressure rise to the north (figs. 11 and 12). From 1200 to 1500 EST on the 3d, the band migrated southward from its position in figure 5 to Adams Center (the dot south of ART in fig. 11). Sykes was near Adams Center when the most intense portion of the snow band passed at 1508 EST. Visibility was reduced to 10 yd. at 1508 EST, and by 1525 EST the storm had passed southward and only flurries remained. Southwest to south-southwest winds during the storm shifted to west in less than 10 min. The snow line continued southward with individual cells moving east-southeastward, leaving behind a 4 in. accumulation of new snow. Figure 11 shows a maximum pressure rise of 0.02 in. over

Watertown (ART) (where the snow band had been at 1200 EST) and a maximum pressure fall of 0.03 in. about 8 n.mi. south of where the heaviest snow was observed at 1508 EST.

Between 0900 and 1200 EST on the 4th (fig. 12), the snow band moved from a Pt. Petre–Isthmus line (60 to 41) to a line between Montario Pt. (28) and Lacona (24). Again, the isallobaric maximum is in the area passed by the band during the 3-hr. period, and the isallobaric minimum is in the area through which the band moved in the succeeding 3 hr. When the band moved rapidly northward from about 0300 to 0500 EST on the 4th, the positions of the isallobaric maximum and minimum were reversed (fig. 13), but the minimum did not appear to lead the line as it did during the southward movements. At 0430 EST, the wind-shift line passed north of Pt. Petre (60) and snow began at Watertown (ART) at 0422 EST. The isallobaric minimum is north of the maximum, but far south of the line's location at the end of the period.

WIND ANALYSIS FOR THE SHORELINE BAND AND DOUBLE BANDS

There are two characteristics of this storm that warrant separate comment.

The subject storm both began and ended as a shoreline band (figs. 3b and 3i). Wind analyses for hours when the band was confined to the south shore of the lake show little difference from those for periods of overlake bands. Though the shoreline bands do appear to depend upon the shoreline for location and orientation, the convergence line and snow have been observed to move inland several miles. Figure 14 shows the wind field for 1500 EST on February 4 (radar photograph fig. 3i). The convergence line and snow had moved south of some shoreline stations and snow had ended at Nine Mile Point (15) and Oswego (11) by this time. Before the storm ended, the wind-shift line moved south of the Niagara Mohawk Whitmore Rd. station (5 mi. south of 15) with a wind shift from 225° to 285°, and Redfield (45) with a shift from 240° to 290°. The only portion of the line over water by 1700 EST was that north of ASRC stations 2 and 5.

Figure 15 shows a particularly interesting feature of the wind field associated with lake effect snow bands. This map corresponds to the period when two separate snow bands existed simultaneously—one through Trenton, Ontario (TR) and the second through Watertown, N.Y. (ART). The streamline analysis is admittedly questionable, especially over the lake, but it appears to be the most reasonable analysis that can be drawn with the data available. There is no doubt about the existence of the double convergence lines, though the wind observations at this time could be interpreted to exclude the western line. Such an interpretation would, however, contradict both the radar and surface data continuity. As the northern snow band approached Trenton, Ontario (TR), the wind backed from 280° to 260°, and the wind records from Pt. Petre (60), Pt. Traverse (58), and Kingston (59) all show both the northwestward and the southeastward passage of a wind-shift line. When the two snow bands merged (fig. 3c), so did their convergence lines, with no observable disturbance in the surface wind field.

5. CONCLUSIONS

We can offer no explanations for the banded structure or the location and movement of lake effect storms based upon the observations and analyses set forth here. One case is insufficient for such speculation, especially without sufficient upper-air observations, temperature data, or observations over the lake. However, certain conclusions do appear warranted by this analysis, personal experience, and previous surface and upper-air macroanalyses performed by McVehil and Peace [9]. The mobility of overlake bands, both in orientation and position over the lake, their formation over the lake, and the possibility of double bands, appear to rule out land breeze, shoreline frictional convergence, or orographic effects as the primary mechanism controlling the shape, location, and movement of these storms. This is not to say that any or all of these effects may not intensify an existing storm once formed through heating of the air by the lake. The orientation of most snow bands approximately along the winds aloft in the cloud layer, the frequent occurrence of simultaneous bands on both Lakes Erie and Ontario that are parallel and move together (as in this case), and the lack of any indication of surface cause in these analyses except the tendency for the isallobaric minimum to lead the band movement, all imply that primary control lies with conditions aloft. Except for the addition of heat and moisture from the lake, the surface conditions appear to be a response, not a cause. It is highly likely that the preference for lake effect storms to form roughly parallel to the long axis of the lakes is only due to a need for the longer overwater trajectory as postulated by Wiggin [17]. The snow bands experienced by the Japanese are very similar to those described here. In Japan they form over the Sea of Japan during cold outbreaks from the Chinese mainland. In those storms there are no shorelines even approximately parallel to the snow bands as there are in lake effect storms.

One consequence of this analysis is the realization that the water surface contributing heat and moisture to the storm is far larger than the area of the storm or individual air trajectories would imply. The heavy snowfall rates typical of these shallow storms (about 8,000 to 10,000 ft. deep) appear possible because of the concentration of moisture into the narrow convergence zone. Here again, further understanding must await better upper-air observations. However, if the dimensions of the surface convergence line are any criterion, truly mesoscale upper-air data will be required.

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